



## Improving stationary and mobile cosmic ray neutron soil moisture measurements

Assessment of the cosmic ray neutron uncertainty and the potential of the thermal neutron signal

Jannis Christoph Jakobi

Energie & Umwelt / Energy & Environment

Band / Volume 578

ISBN 978-3-95806-628-1

Forschungszentrum Jülich GmbH  
Institut für Bio- und Geowissenschaften  
Agrosphäre (IBG-3)

## **Improving stationary and mobile cosmic ray neutron soil moisture measurements**

Assessment of the cosmic ray neutron uncertainty and the  
potential of the thermal neutron signal

Jannis Christoph Jakobi

Schriften des Forschungszentrums Jülich  
Reihe Energie & Umwelt / Energy & Environment

Band / Volume 578

---

ISSN 1866-1793

ISBN 978-3-95806-628-1

# Contents

<b>Abstract</b> .....	<b>i</b>
<b>Zusammenfassung</b> .....	<b>v</b>
<b>Contents</b> .....	<b>ix</b>
<b>List of Figures</b> .....	<b>xi</b>
<b>List of Tables</b> .....	<b>xviii</b>
<b>List of Abbreviations</b> .....	<b>xix</b>
<b>List of Symbols</b> .....	<b>xxi</b>
<b>1 Motivation and general introduction</b> .....	<b>1</b>
1.1 The relevance of soil moisture content .....	2
1.2 The measurement of soil moisture content .....	2
1.2.1 Scales of soil moisture content measurements .....	2
1.2.2 Point scale soil moisture content measurements .....	4
1.2.3 Air- and spaceborne remote sensing of soil moisture content.....	5
1.2.4 “Classical” non-invasive soil moisture content measurement techniques .....	6
1.2.5 Emerging non-invasive soil moisture content measurement techniques.....	7
1.3 Cosmic ray neutron sensing .....	9
1.4 Objectives and outline.....	13
<b>2 Error estimation for soil moisture measurements with cosmic ray neutron     sensing and implications for rover surveys</b> .....	<b>15</b>
2.1 Introduction .....	16
2.2 Material and Methods .....	18
2.2.1 Jülich CRN rover.....	18
2.2.2 Experimental sites .....	19
2.2.3 Data acquisition and standard processing .....	22
2.2.4 Conversion of neutron counts to soil moisture content.....	23
2.2.5 Quantification of measurement accuracy .....	24
2.2.6 Expected measurement accuracy due to uncertain neutron count rates .....	24
2.2.7 Other sources of uncertainty.....	26
2.2.8 Neutron aggregation strategies .....	27
2.3 Results and Discussion.....	28
2.3.1 Expected accuracy – Analytical vs. Monte Carlo approach.....	28
2.3.2 Experiment A (Fendt site).....	31
2.3.3 Experiment B (Selhausen site) .....	34
2.3.4 Experiment C (Oklahoma site).....	37
2.4 Conclusion and Outlook.....	40
<b>3 The footprint characteristics of cosmic ray thermal neutrons</b> .....	<b>43</b>
3.1 Introduction .....	44
3.2 Material and Methods .....	45
3.2.1 River experiment .....	45
3.2.2 Neutron transport modeling.....	46
3.2.3 Evaluation of model results.....	46
3.3 Results .....	47
3.3.1 River experiment .....	47
3.3.2 Horizontal thermal neutron footprint .....	49

3.3.3 Vertical thermal neutron footprint.....	51
3.4 Discussion .....	52
3.5 Conclusions and Outlook .....	54
<b>4 Potential of thermal neutrons to correct cosmic ray soil moisture content measurements for dynamic biomass effects .....</b>	<b>55</b>
4.1 Introduction .....	56
4.2 Materials and Methods.....	58
4.2.1 The Selhausen experimental site .....	58
4.2.2 Auxiliary meteorological data .....	59
4.2.3 In-situ soil moisture content measurements .....	59
4.2.4 In-situ soil sampling .....	60
4.2.5 Weighting of reference measurements .....	60
4.2.6 Biomass measurements .....	61
4.2.7 Cosmic Ray Neutron Measurements .....	62
4.2.8 The thermal-to-epithermal neutron ratio .....	64
4.2.9 Conversion of neutrons to soil moisture content.....	64
4.2.10 Biomass, $N_r$ , and thermal neutron corrections .....	65
4.3 Results .....	66
4.3.1 Data Overview .....	66
4.3.2 The effect of time-variable biomass on CRNS derived soil moisture content ..	69
4.3.3 Soil moisture content correction with local biomass measurements.....	70
4.3.4 Soil moisture content correction with the neutron ratio .....	72
4.3.5 Soil moisture content correction with thermal neutrons .....	74
4.3.6 Biomass estimation from the neutron ratio .....	75
4.3.7 Biomass estimation from thermal neutrons .....	77
4.4 Discussion .....	79
4.4.1 Correction of biomass effects on soil moisture content estimates with CRNS ..	79
4.4.2 Biomass estimation with CRNS .....	81
4.4.3 Vegetation influence on neutron intensities .....	82
4.5 Conclusions and Outlook .....	82
<b>5 Synopsis.....</b>	<b>85</b>
5.1 Final summary and conclusions .....	86
5.2 Outlook and preliminary work .....	89
5.2.1 Example 1: Long-term vegetation monitoring with thermal neutrons .....	92
5.2.2 Example 2: Value and limits of CRN rover observations .....	95
<b>Appendix.....</b>	<b>101</b>
Appendix I: Standard processing .....	101
Appendix II: Thermal neutron footprint - weighting functions and parameters .....	103
Appendix III: Dependency of the thermal neutron footprint on detector height .....	105
Appendix IV: Hysteresis in the sugar beet experiment.....	107
Appendix V: Comment on Dong and Ochsner (2018): “Soil Texture often Exerts stronger Influence Than Precipitaion on Mesoscale Soil Moisture Patterns”.....	109
<b>Bibliography .....</b>	<b>115</b>
<b>Acknowledgements .....</b>	<b>133</b>
<b>Publications .....</b>	<b>137</b>

Energie & Umwelt / Energy & Environment  
Band / Volume 578  
ISBN 978-3-95806-628-1

Mitglied der Helmholtz-Gemeinschaft

